Anomalous Temperature and Disorder Dependence of the Electron-Phonon Scattering Time in Impure Metals

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Abstract

We have measured the electron-phonon scattering time, τ_{ep}, in disordered metals at liquid-helium temperatures, using weak-localization method. The temperature and disorder dependence of τ_{ep} is determined for AgPd and AuPd thick films, and $V_{100-x}Al_x$ alloys. In all three cases, we find an anomalous temperature and disorder dependence of $\tau_{ep}^{-1} \propto T^2\ell$, where ℓ is the electron elastic mean free path. This temperature and disorder behavior cannot be explained in terms of current theoretical concepts for the electron-phonon interaction in impure conductors. Current theory predicts a form of either $\tau_{ep}^{-1} \propto T^4\ell$ or $\tau_{ep}^{-1} \propto T^2\ell^{-1}$ in the dirty limit, depending on the nature of the defects.

Key words: electron-phonon interaction; impure conductors; weak localization

The electron-phonon (e-ph) interaction in impure conductors is a long-standing problem in condensed-matter physics. The e-ph scattering time, τ_{ep}, in the presence of *multiple* elastic impurity scattering has been calculated by several authors for over decades [1–3], but our understanding of the temperature and electron elastic mean free path, ℓ, dependences of τ_{ep} is still incomplete. Theoretically and experimentally, different temperature and disorder dependences of τ_{ep} have been reported in the literature [4,5]. The situation becomes even less clear in the case of reduced-dimensional systems where the effect of phonon confinement may further complicate the problem. Information about the temperature and mean-free-path dependences of τ_{ep}^{-1} will undoubtedly shed light on our understanding of the microscopic interactions of the e-ph process.

In addition to the electron heating measurements [6], systematic information about $\tau_{ep}(T,\ell)$ can be experimentally obtained from weak-localization (WL) studies, using carefully selected, tailor-made samples covering a wide range of material characteristics [4,5]. In *three* dimensions, the total electron dephasing rate that governs the WL effects is given by [7,8]

$$\frac{1}{\tau_\phi(T,\ell)} = \frac{1}{\tau_\phi^0} + \frac{1}{\tau_{ep}} = \frac{1}{\tau_\phi^0(\ell)} + A_{ep}(\ell)T^p\,, \qquad (1)$$

where $\tau_\phi^0 = \tau_\phi(T \to 0)$ depends very weakly on temperature, if at all, and is called the saturated dephasing time [5]. The second term in Eq. (1) is due to the e-ph scattering, where A_{ep} characterizes the strength of e-ph coupling, and p is an effective exponent of temperature.

In order to improve our understanding of the e-ph interaction in disordered metals, we have in this work measured τ_{ep} in a few series of RF sputtered AgPd, and DC sputtered AuPd thick films, and arc-melted $V_{100-x}Al_x$ alloys. Our samples are polycrystalline, and they are three-dimensional with regard to the electron dephasing length $\sqrt{D\tau_\phi}$, where D is the diffusion constant, that determines the system dimensionality in the WL problem. For each sample, low-field magnetoresistivities between 0.5 and 20 K are measured and compared with three-dimensional WL theoretical predic-

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tions [7] to extract the value of τ_ϕ. The extracted τ_ϕ is then least-squares fitted to Eq. (1), yielding the values of A_{ep} and p.

We first discuss our experimental temperature dependence of τ_{ep}^{-1}. For *all* samples, the value of p that we obtained in the above manner is equal or close to 2, suggesting that the experimental e-ph scattering rate is best described with an essentially quadratic temperature dependence (not shown). A quadratic temperature dependence of τ_{ep}^{-1} in disordered metals has remained a lasting puzzle for over years [5]. Recently, anew theoretical efforts aiming at resolving this puzzle have been proposed in Refs. [9] and [10].

In addition to the temperature dependence, the ℓ dependence of τ_{ep}^{-1} is indispensable in gaining a full explanation of the e-ph interaction in impure conductors. In each series of samples studied in this work, we have "tuned" the amount of disorder (i.e., the residual resistivity $\rho_0 = \rho(10\,\mathrm{K})$) by progressively adjusting the fabrication conditions. In the cases of AgPd and AuPd thick films, the value of ρ_0 was tuned by varying the deposition rate; while in the case of $V_{100-x}Al_x$ alloys, the value of ρ_0 was tuned by varying the Al concentration x from 18 to 26. Within this range of x, the $V_{100-x}Al_x$ alloys remain single-phased. Our values of ρ_0 are 70−180, 70−230, and 140−210 $\mu\Omega$ cm for AgPd, AuPd, and $V_{100-x}Al_x$, respectively.

What is most striking is that, with the values of A_{ep} extracted for each series of samples covering a sufficiently wide range of ρ_0, we observe a totally unexpected linear dependence of τ_{ep} on disorder, i.e., $\tau_{ep} \propto \rho_0$. We find that such a linearity holds for all the AgPd, and AuPd thick films, and $V_{100-x}Al_x$ alloys studied. Figure 1 shows a representative plot of the extracted value of A_{ep} as a function of the reciprocal of ρ_0 for a series of 4000−5000 Å thick AgPd films. This figure clearly reveals that $A_{ep} \propto \rho_0^{-1}$, i.e., $\tau_{ep}^{-1} \propto \ell$. Taken together, the observation of Fig. 1 with the above-mentioned T^2 temperature dependence, our result demonstrates an anomalous $\tau_{ep}^{-1} \propto T^2\ell$ behavior. For a given resistivity of $\rho_0 = 150$ $\mu\Omega$ cm, we obtain $\tau_{ep}(1\,\mathrm{K}) \approx 1.2\times10^{-8}$, 2.5×10^{-10}, and 1.3×10^{-9} s in AgPd, AuPd, and $V_{100-x}Al_x$, respectively.

According to the "orthodox" e-ph interaction theory for disordered metals [1–3], that assumes a coherent motion of the impurity atoms with the deformed lattice atoms at low temperatures, one should expect a $\tau_{ep}^{-1} \propto T^4\ell$ dependence. Recently, it was speculated that, in real metals containing heavy (light) impurities, the impurity atoms might not move in phase with the lattice atoms [11]. The first calculations in consideration of this effect have been done in Ref. [9]. It was found that even a small amount of "static" potential scatterers drastically changes the e-ph-impurity interference, and the relaxation rate is proportional to T^2L^{-1}, where L is the electron mean free path with respect to the static impurities ($L \gg \ell$). Experimentally, a T^4 dependence has been observed very recently, in disordered Hf and Ti thin films [12]. However, to the best of the authors' knowledge, the combined $T^4\ell$ law has *never* been found in any real conductors thus far. On the other hand, a distinct $\tau_{ep}^{-1} \propto T^2\ell^{-1}$ dependence has been observed in $Ti_{100-x}Al_x$ and $Ti_{100-x}Sn_x$ alloys [13]. Previously, a $T^2\ell$ dependence has been observed in two-dimensional Nb *thin* films [14].

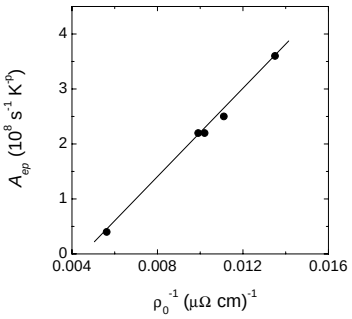

Fig. 1. Variation of A_{ep} with ρ_0^{-1} for AgPd thick films. The straight line drawn through the data is a guide to the eye.

In conclusion, we have found extensive evidence of a $T^2\ell$ temperature and disorder dependence of τ_{ep}^{-1} in AgPd, and AuPd thick films, and $V_{100-x}Al_x$ alloys. This $T^2\ell$ behavior is unexpected, even qualitatively, in terms of the current theoretical concepts for the e-ph interaction in impure conductors.

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